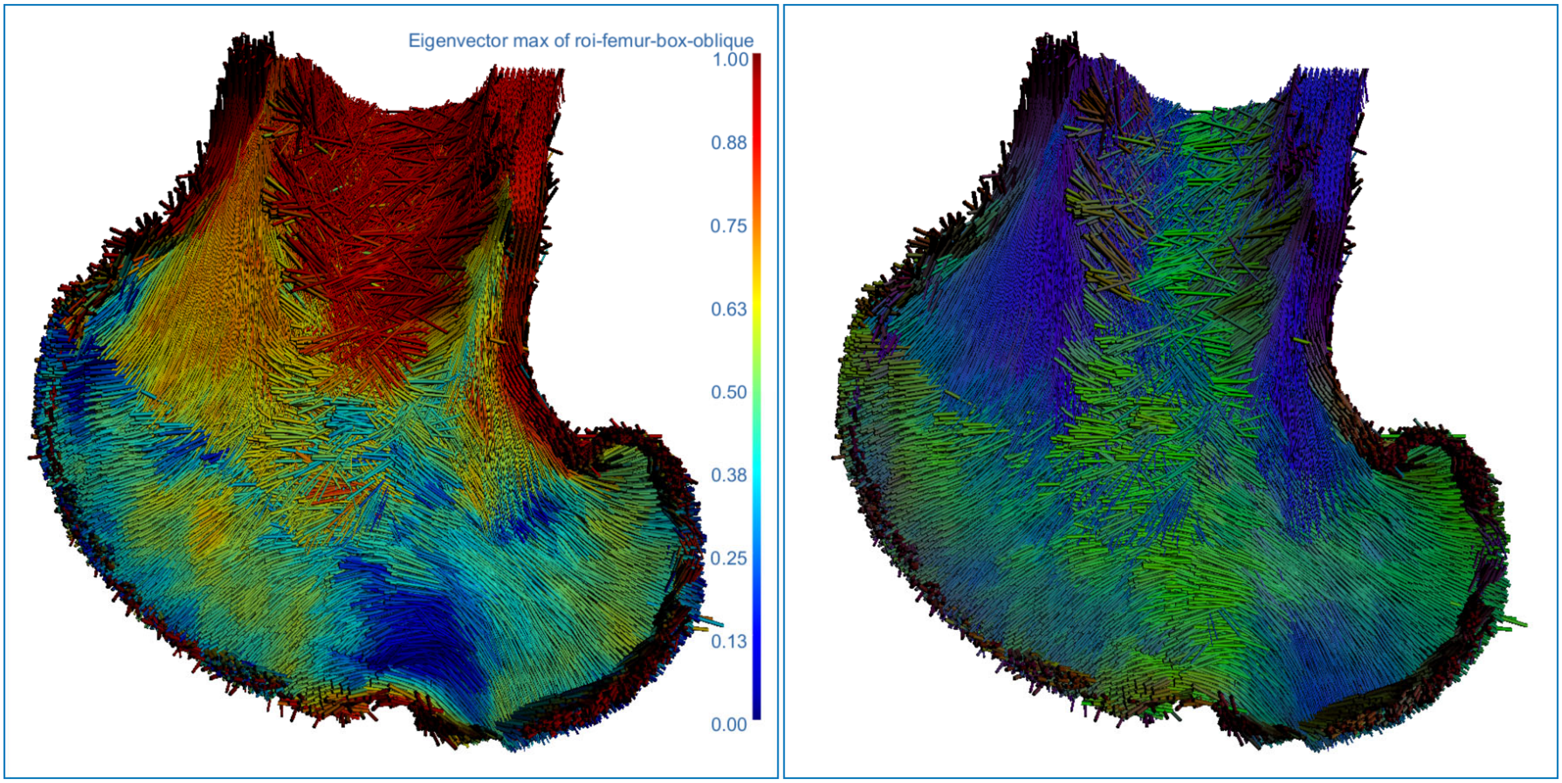

Dragonfly Bone Analysis

Trajectories of Human Trabecular Bone Adaptation within a 4D Landscape of Tissue Anisotropy

Trajectories of Human Trabecular Bone Adaptation within a 4D Landscape of Tissue Anisotropy

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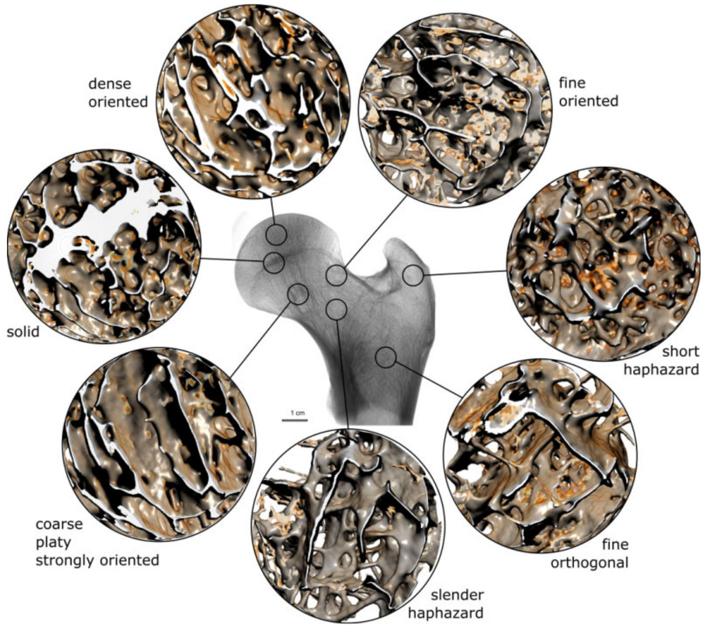
Introduction

Anisotropy (Greek: "an" - non; "iso" - equal; "tropos" - way), the opposite of isotropy, is a property of having texture or preferred orientation of the components within a whole structure.

Anisotropy of trabecular bone is a result of life-long functional adaptation. Anisotropy physiologically increases from infancy to adulthood, and it is more pronounced in the sites where mechanical loading is predictable, consistent and strenuous. For joints, a narrower range of movement results in higher trabecular anisotropy: the most relevant directions are reinforced which results in more oriented trabecular texture. Besides these general biomechanical factors, local features such as muscle attachments, vascular canals or vestiges of the growth plate (metaphyseal scar) may alter tissue fabric and contribute to tissue inhomogeneity. For this reason, we present an approach for mapping independent descriptors of trabecular bone tissue within an entire anatomical entity, and for relating observed variations to bone mechanical function in life.



Local variations of trabecular bone texture within a single specimen; human proximal femur

Approach

The pathways leading to local change in anisotropy include 1) preferential distribution of the volume ("volume anisotropy"), or 2) preferential alignment of the bone-marrow interface ("surface anisotropy"). Both volume and surface anisotropy may synergistically contribute to the higher net anisotropy (if both follow the same direction), or they may negate each other (if they follow different directions). The classic method of anisotropy measurement using Mean Intercept Length (MIL) combines both surface and volume anisotropy components and requires the sampling volume to be about 4-5 intertrabecular spaces. The pure surface anisotropy measurement (as developed by Object Research Systems Inc.) is based on construction of a surface mesh populated by a set of vectors perpendicular to the mesh faces with their magnitude being proportional to the local mesh face area (S). Coefficient of Anisotropy (CA,≥1) is converted into Degree of Anisotropy (DA) for the sake of normalization. Local surface anisotropy, i.e., purely surface orientation in 3D, is calculated with a sampling volume radius of approximately 0.5 mm or more, using a vector operation and projection of the face normals (n) on the principal axis (I) associated with the eigenvectors of the inertia tensor.

$$\mathrm{CA} = \frac{\sum_{i \in \text{faces}} S_i \cdot \|\vec{n}_i \times \vec{I}_0\|}{\sum_{i \in \text{faces}} S_i \cdot |\vec{n}_i \cdot \vec{I}_0|} - 1; \quad \mathrm{DA} = 1 - 1/\mathrm{CA}$$

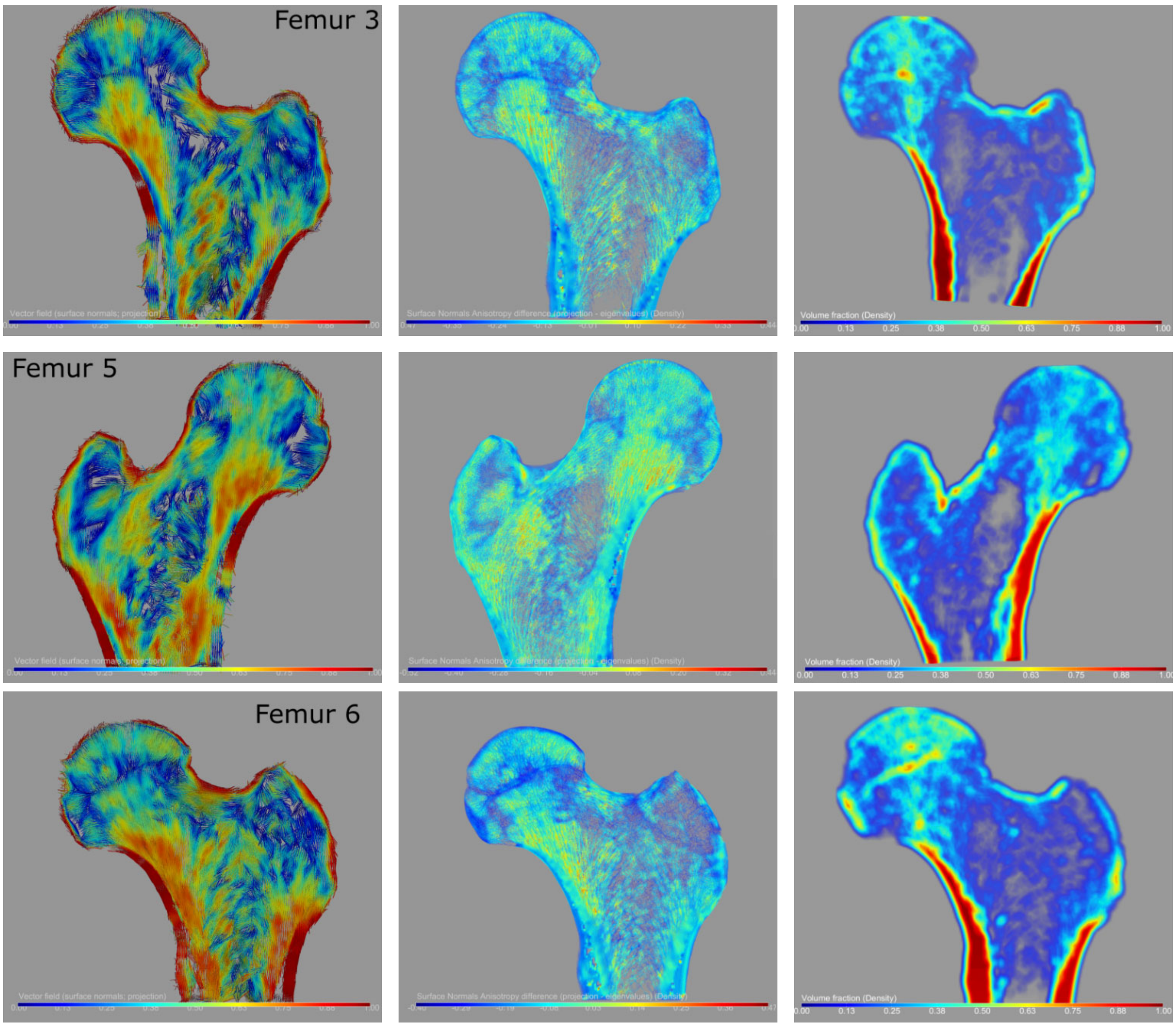
A perfectly isotropic surface (as of a sphere) gives 0, and a perfectly anisotropic surface (as of an infinite line) gives 1. Local volume anisotropy is the material distribution in 3D, regardless of the surfaces/interfaces orientation. For example thick or thin elements having random or textured organization may result in, respectively, low or high volume anisotropy. Volume anisotropy is essentially a difference between the local eigenvalue-based anisotropy magnitude and local surface anisotropy magnitude, since both use the same surface mesh and same sampling radius. Both local surface anisotropy magnitude and directionality can be displayed as vector fields using a color scale to represent vector magnitude and orientation (RGB, red - X, green - Y, blue - Z). These maps are compared to the scalar maps of the local volume anisotropy (volume distribution) and bone volume fraction.

Aim

To map the surface anisotropy (magnitude and directionality) as vector fields, and the volume anisotropy and volume fraction as scalar fields across an entire anatomical entity in order to identify heterogeneity, latent features and to correlate form with function in bone.

Case Study 1 - Proximal femur

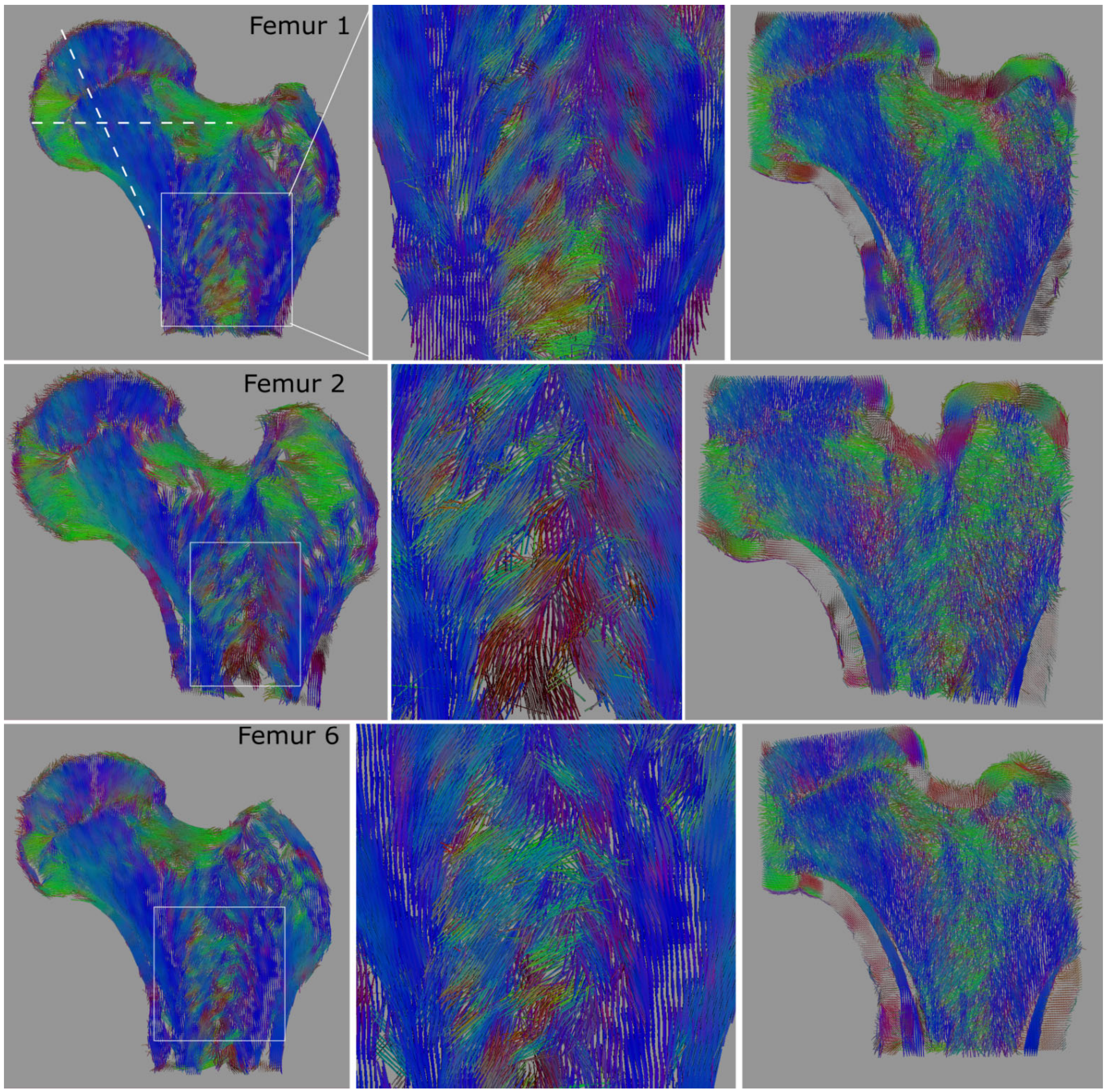
Surface anisotropy (magnitude) | Volume anisotropy | Volume fraction



- Strongest surface anisotropy colocalizes with strongest volume anisotropy.
- Strongest volume anisotropy does not colocalize with highest volume fraction.
- Highest volume fraction projects on the zenith of the femoral head.
- Strongest anisotropy is limited to the metaphysis.

Case Study 1 - Proximal femur (continued)

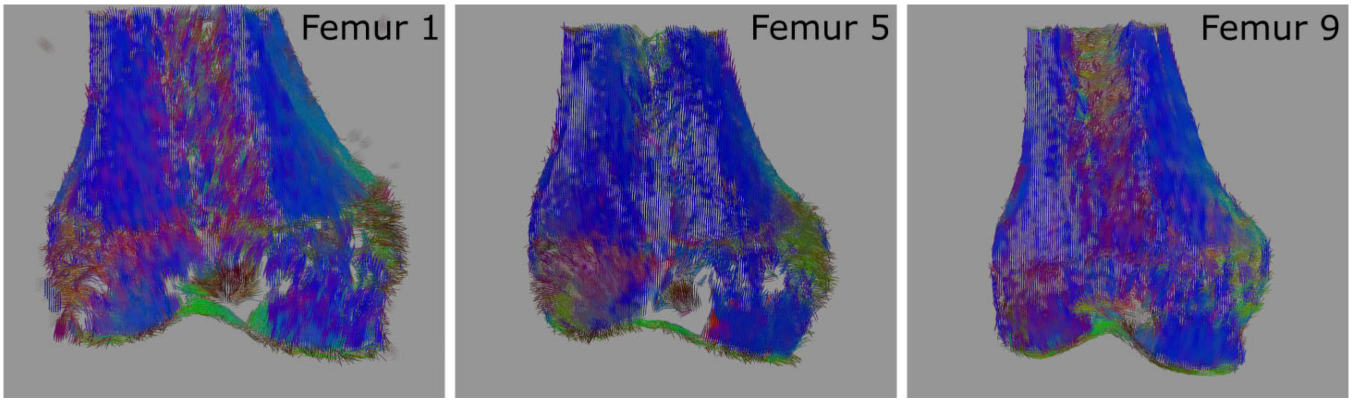
Surface anisotropy (directionality)	**Zoom-in on metaphysis**	**Conventional MIL anisotropy (directionality)**



- Surface anisotropy computation allows higher-resolution mapping in comparison with conventional MIL anisotropy (the latter being confined to the minimal sampling volume).
- Surface anisotropy directionality maps highlight criss-crossing trajectories (dashed lines) in the femoral neck and head region.
- Surface anisotropy map identifies a patchy "braided" pattern in the metaphysis.

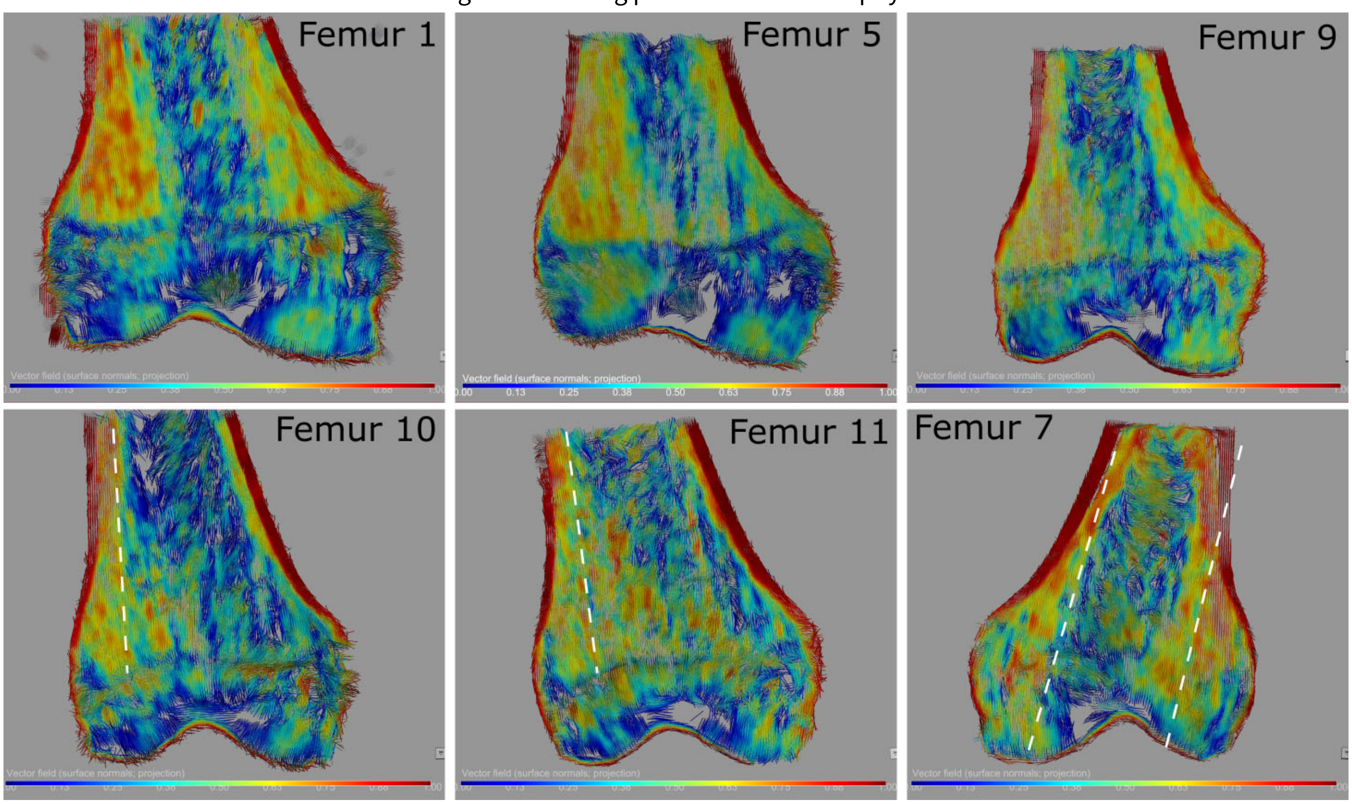
Case Study 2: Distal femur

Surface anisotropy (directionality)



- Surface anisotropy directions are mainly confined to the vertical (blue) and antero-posterior (red) orientations, consistent with the range of movement in the knee.

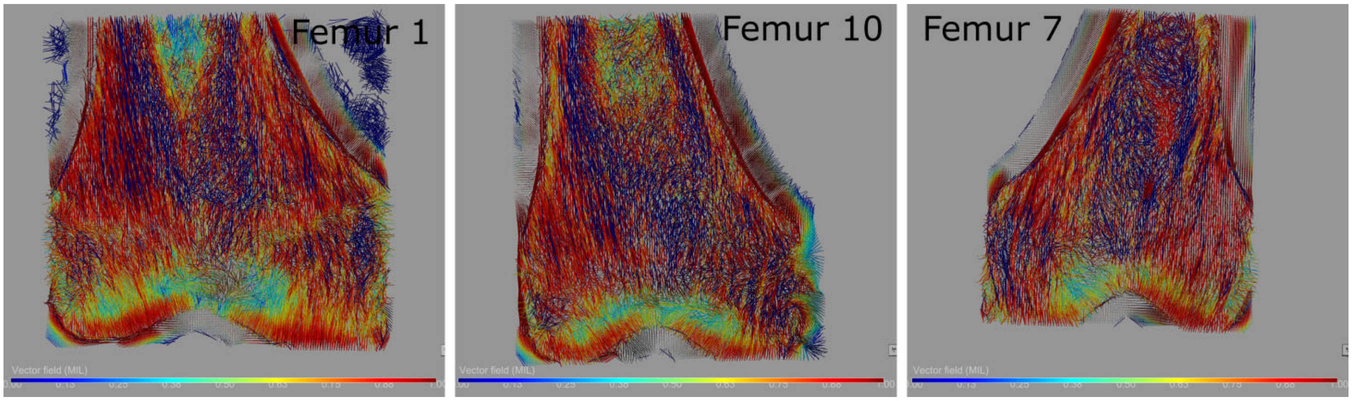
Surface anisotropy (magnitude): samples 1, 5, 9, 10, 11 and 7 are arranged according to decreasing prominence of metaphyseal sca



- Surface anisotropy plotted by magnitude forms stress trajectories perpendicular to the articular surfaces of the medial and lateral condyles (dashed lines).
- Where metaphyseal scar is present, the highest anisotropy values are confined to the metaphysis and do not cross the scar demarcation.

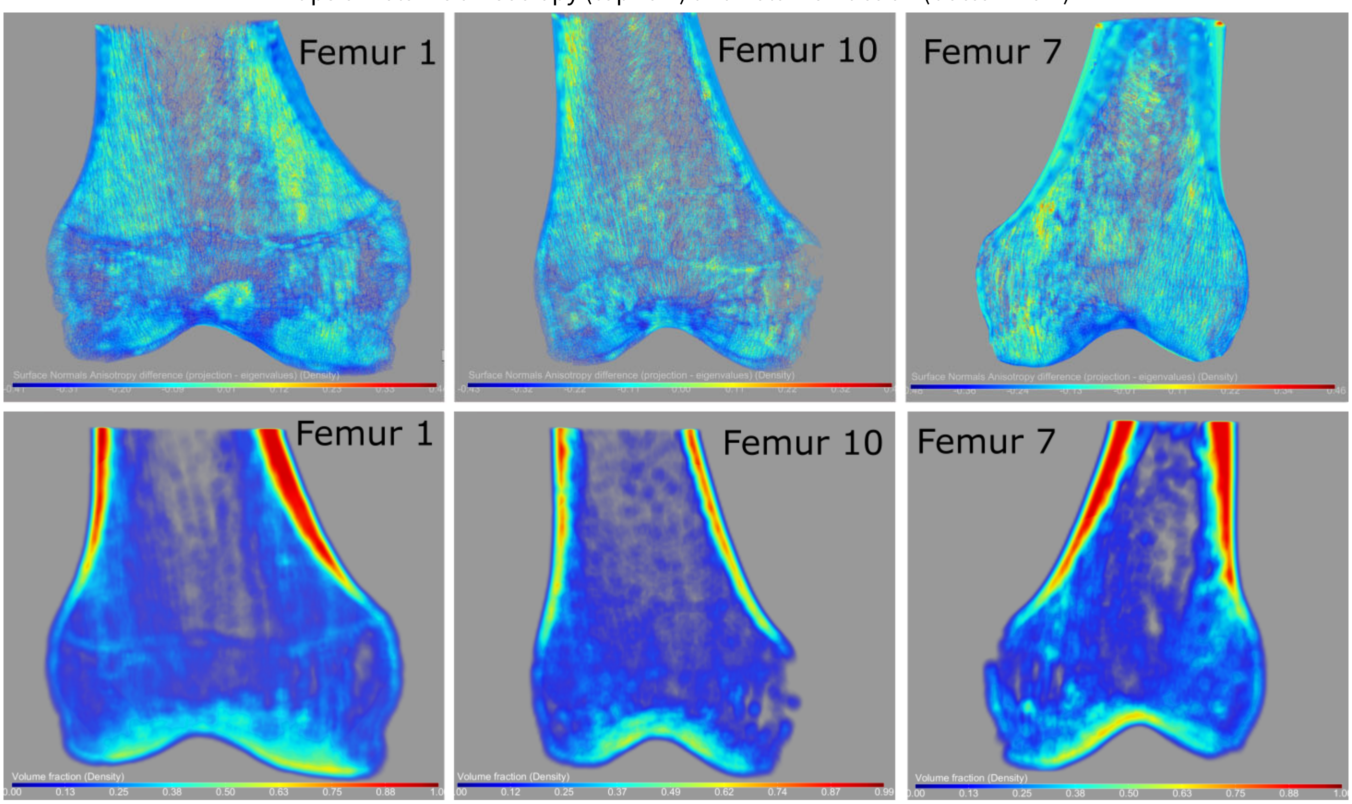
Case Study 2 - Distal femur (continued)

Conventional MIL anisotropy (magnitude)



- MIL anisotropy map captures sample homogeneity but fails to highlight inter- and intra-individual variation (e.g., medial versus lateral portion, or metaphyseal versus epiphyseal portion).
- Due to the inherently high sampling volume, MIL anisotropy is sensitive to edge effects.

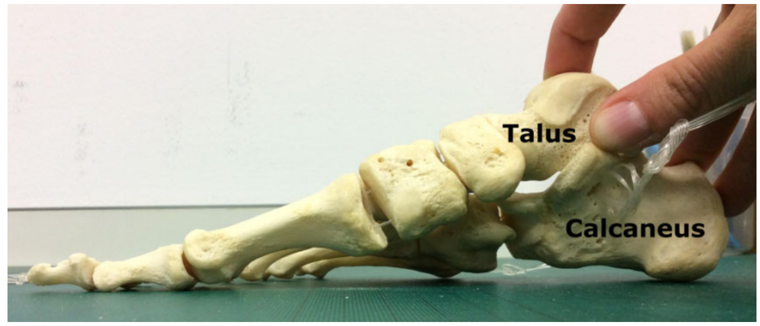
Maps of volume anisotropy (top row) and volume fraction (bottom row)



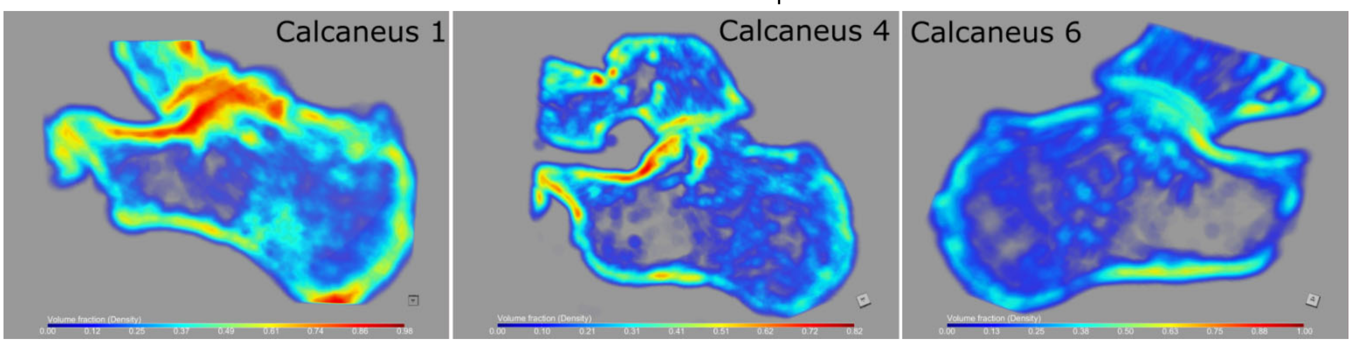
- Volume anisotropy in the distal femur is not colocalized with the highest volume fraction.
- Volume anisotropy is generally less pronounced in the distal femur than in the proximal femur.
- Volume anisotropy follows but does not precisely colocalize with surface anisotropy.

Case Study 3: Calcaneus

The calcaneus is the largest of the 7 tarsal bones of the foot. It articulates with the talus above and the cuboid anteriorly, forming the shock-absorbing foot arch. Its distal portion, the tuberosity, is balanced between the Achilles tendon and the plantar fascia and bears roughly 40% of the load in bipedal locomotion.

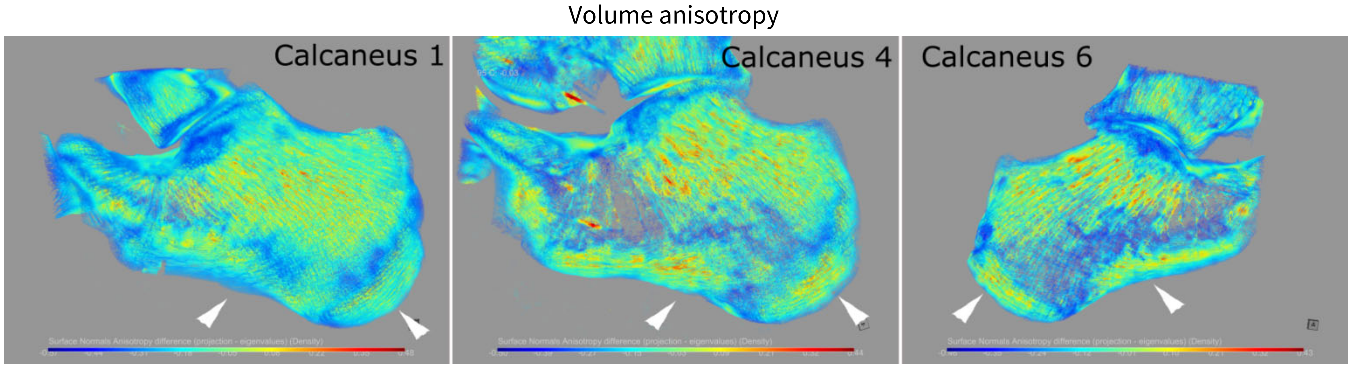


Volume fraction map



- In comparison to the distal or proximal femur, the calcaneus has the lowest volume fraction which is nevertheless sufficient for its heavy-duty performance, and that is apparently dictated by its shock-absorbing function.
- As opposed to the distal and proximal femur, the highest volume fraction (red-orange) is localized at the articulating surfaces.

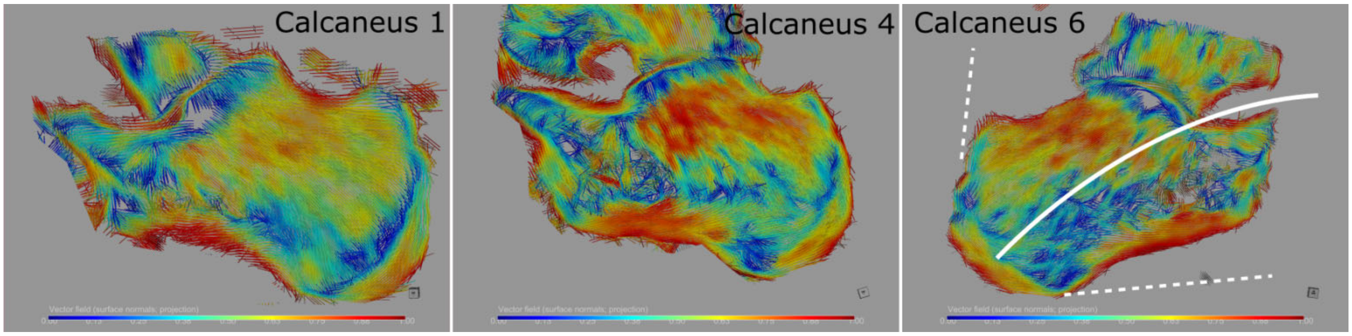
Volume anisotropy



- Volume anisotropy contribution to total anisotropy is pronounced in the calcaneus (yellow-orange).
- The strongest volume anisotropy is colocalized with the highest volume fraction on the plantar surface of the calcaneus and in the tuberosity area, arrowheads.

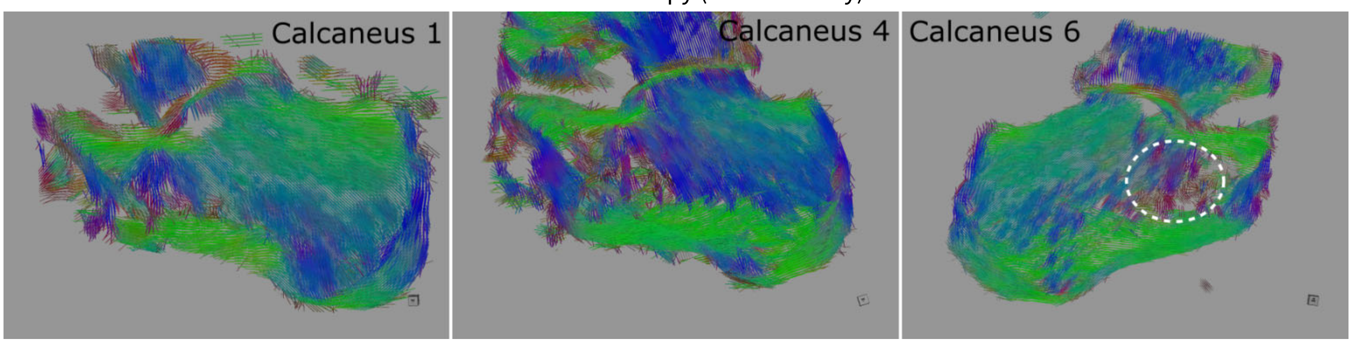
Case Study 3 - Calcaneus (continued)

Surface anisotropy (magnitude)



- Surface anisotropy reflects the major stress trajectories in the foot: compression of the arch (solid line) and tensile action of the plantar fascia and Achilles tendon (dashed lines).

Surface anisotropy (directionality)



- Surface anisotropy is most diverse in the foot, in comparison to the femur sites.
- The transverse component (red) correctly identifies in 3D the off-plane orientation of the sustentaculum tali (dashed circle).

Conclusions

- This novel algorithm for volumetric mapping is suitable for analysis of entire bones in 3D with a resolution down to 0.5 mm.
- The 4 parameters presented here, two vector-based (surface anisotropy magnitude and directionality) and two scalar-based (volume anisotropy and volume fraction) are independent and reflect the biomechanical circumstances applied to a given bone.
- This method for mapping and 3D characterization of bone structure discloses regional variations, exact structure-function relationships and adaptational pathways.

Acknowledgements

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